Implementation of in-situ Measurement Techniques for Plasma Processing

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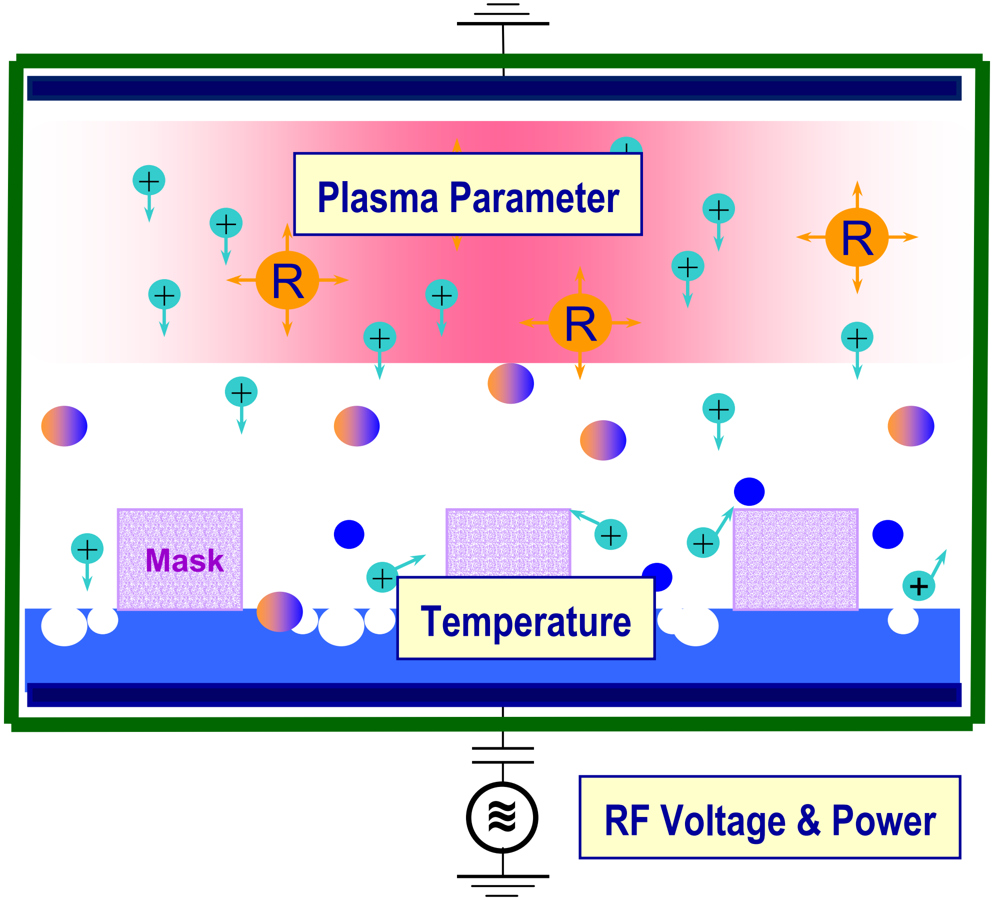
Outline

- **Examples of in-situ Measurement Techniques to improve Plasma Process Control**
  - RF Voltage and power measurement
  - Wafer temperature measurement
  - Plasma parameter measurement by SEERS
- Implementation of in-situ measurement techniques into high volume production
- Application of in-situ measurement techniques into high volume production
- Correlation of tool, process and product parameters
- Summary

Plasma Processing



Chamber ← Toolbox

Plasma ← Tool:
non-equilibrium
non-linear

Transport processes:
non-linear

Reactions on wafer:
non-equilibrium chemistry

- ❑ Needed: Sufficient measurement and control of surface conditions on product wafers in real time. - This is not possible.

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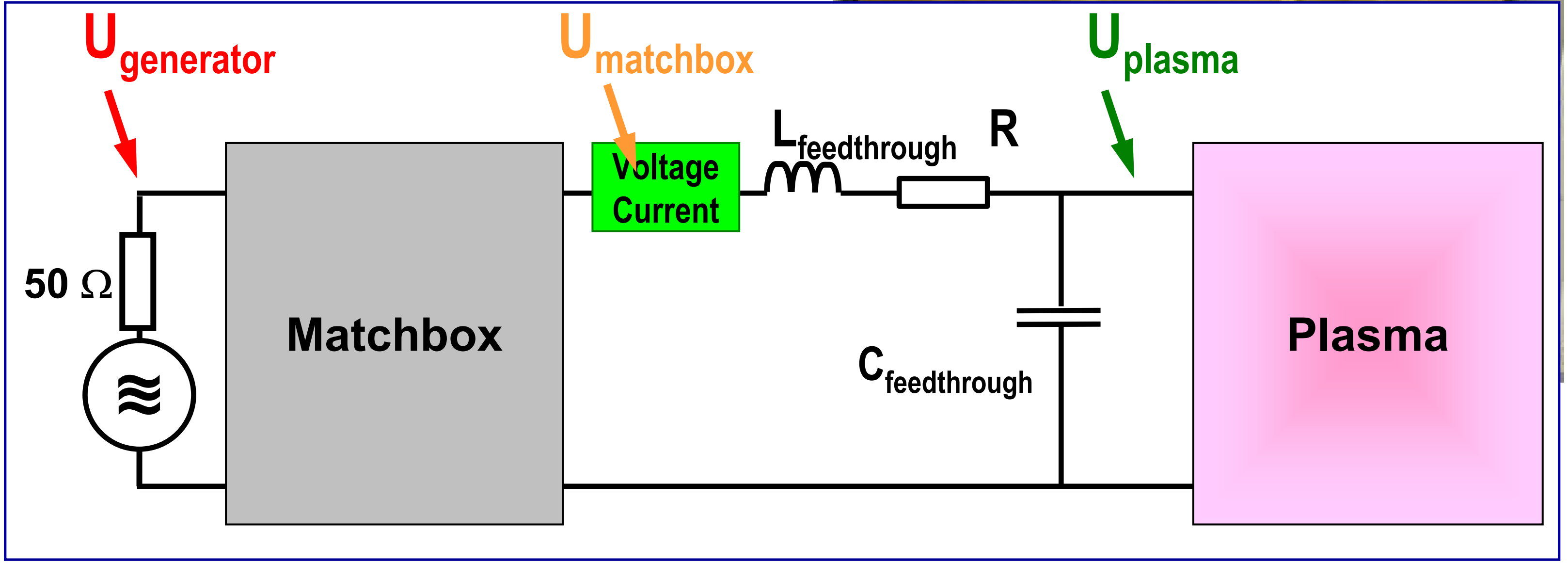
First Method:
RF Voltage and Power Measurement

- Improvement of RF power measurement:
  - Standard method: at generator output $U_{generator}$
  - Now available: at matchbox output $U_{matchbox}$
  - Needed: at plasma U_{plasma}



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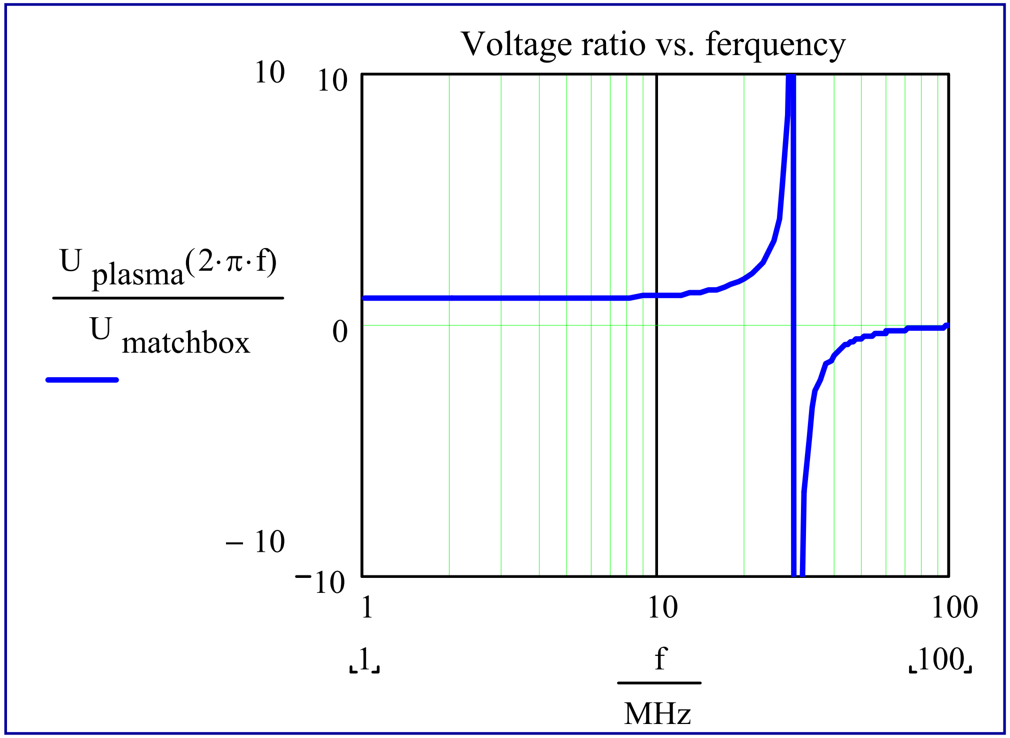
Resonance Impact on RF Voltage and Power Measurement



$$U_{plasma}(\omega) := U_{matchbox} \frac{1}{1 - \omega^{2} \cdot C_{feedthrough} \cdot L_{feedthrough}}$$

- Significant difference between U_{plasma} and $U_{matchbox}$ around and above chamber resonance frequency

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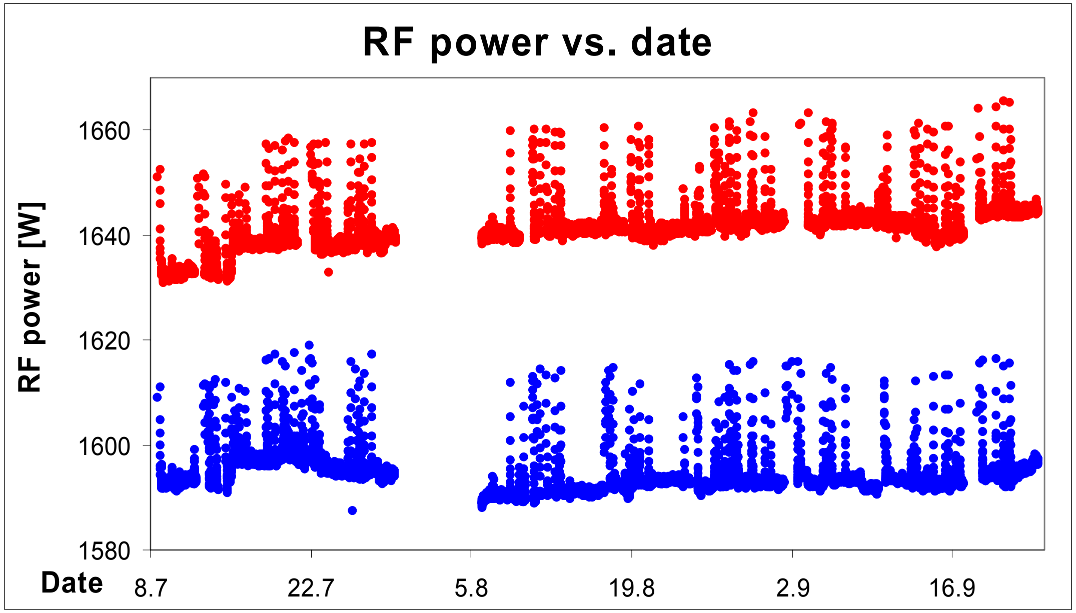
RF Power Measurement at RF Matchbox Output: Application on Chamber Matching

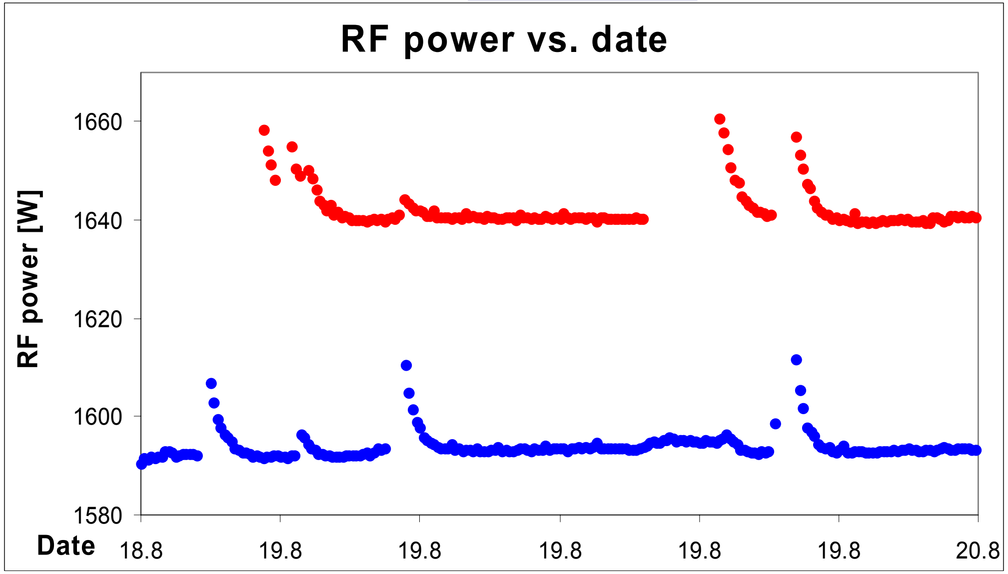
➔Poster P511



- ❑ Generator output power: 1800W
- ❑ Power loss depends on chamber

Chamber A
Chamber B

- ❑ Drift of power at RF matchbox output
- ❑ Estimated root cause: RF matchbox thermal drift



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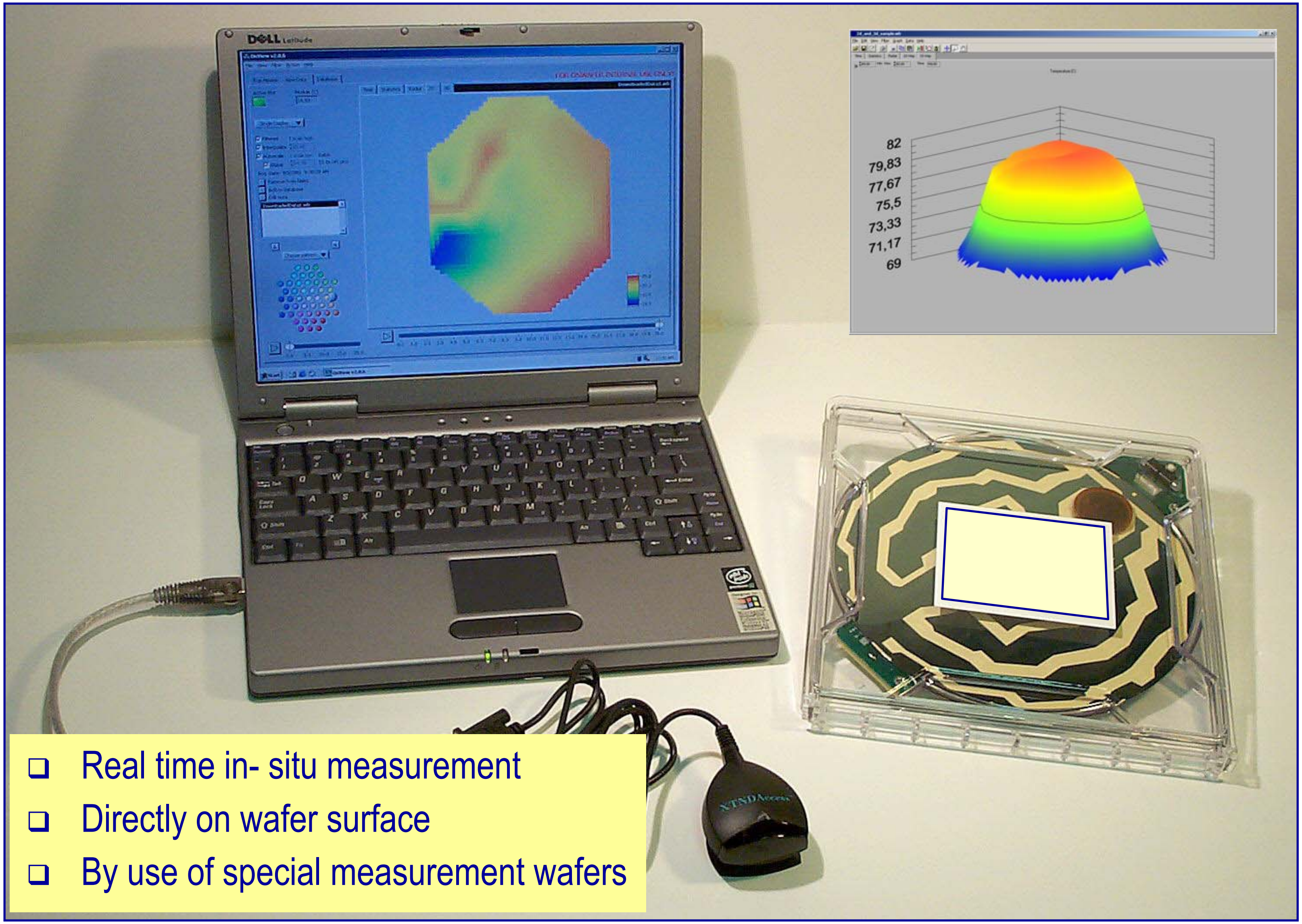
14.04.2004

Second Method:
Wafer Temperature Measurement



- ☐ Real time in- situ measurement
- ☐ Directly on wafer surface
- ☐ By use of special measurement wafers

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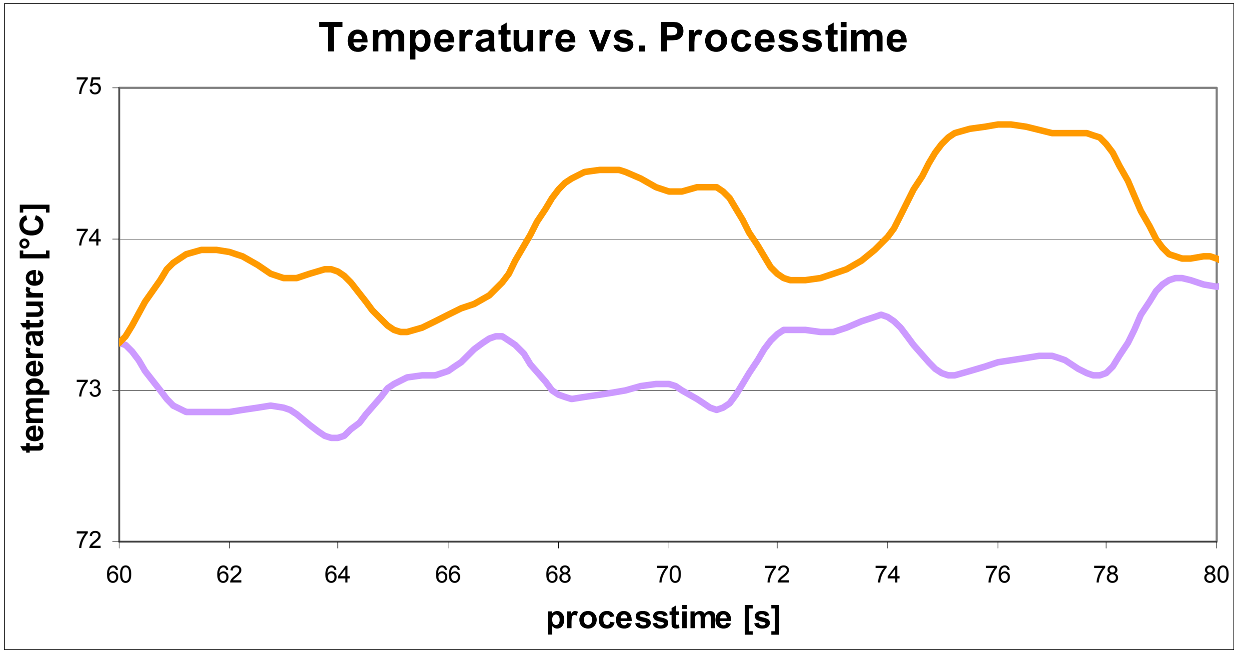
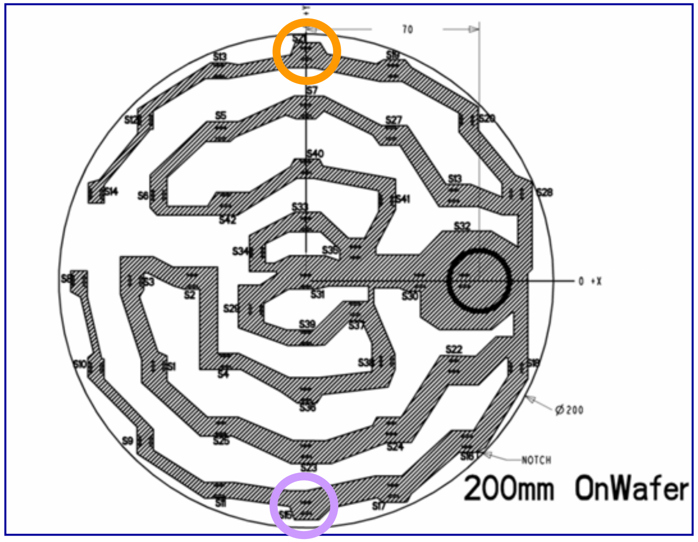
Application Example: Impact of Rotating B- Field on Wafer Surface Temperature

➔Poster P513



- ❑ Time resolved local wafer surface temperature measurement demonstrates impact of rotating B-Field
- ❑ Details on poster P513



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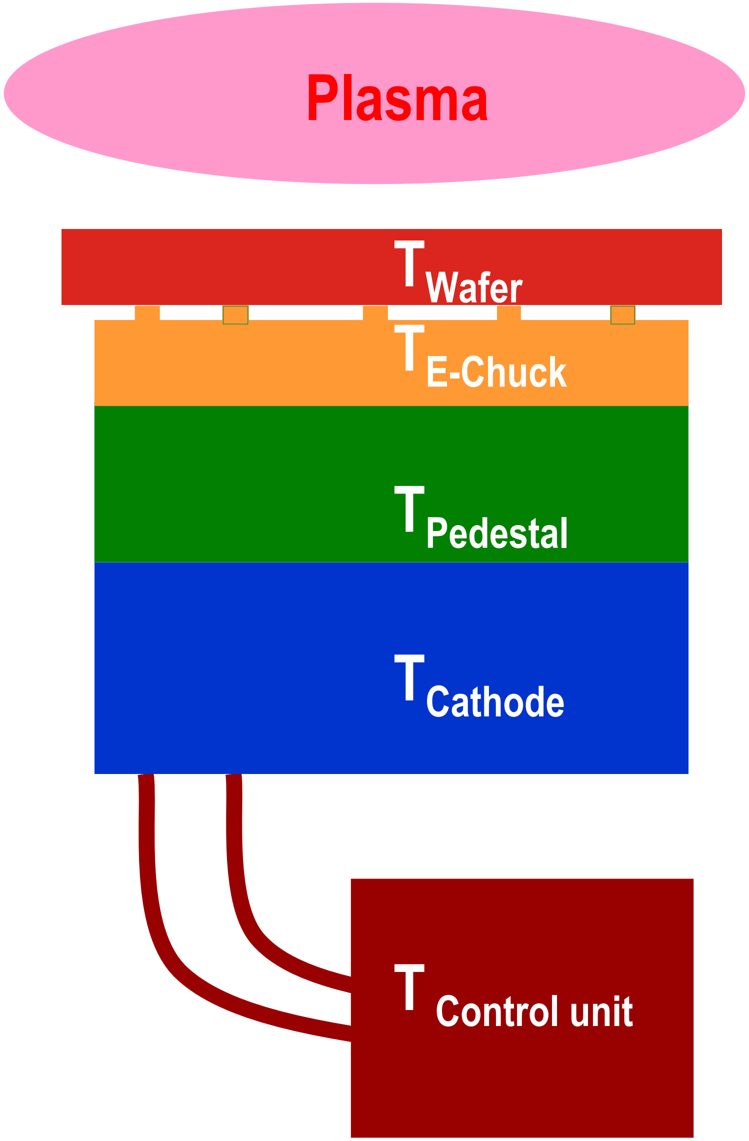
Application Example: Improvement of Wafer Temperature Control

➔Poster P505

- Temperature control:
  - Temperature measurement at pedestal
  - Temperature control of cooling liquid at control unit
- Improvement:
  - Simulation of thermal flow, details on poster P505
  - Wafer surface temperature measurement by test wafer is used for model calibration
  - → Model based adjustment of control unit temperature



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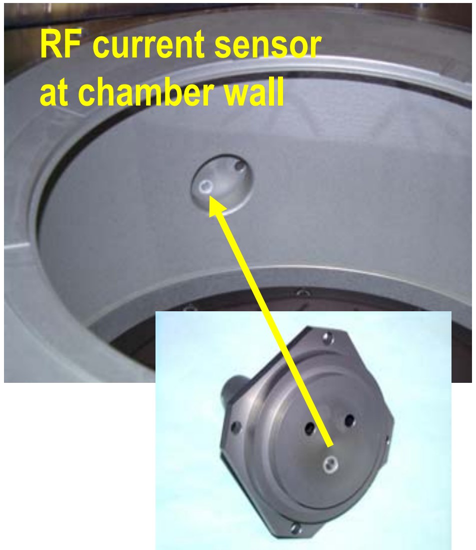
Third Method:
SEERS Plasma Parameter Measurement

RF current & voltage measurement

Real time calculation Model SEERS

Plasma parameters



- ❑ up to 500 MHz
- ❑ Passive measurement → no impact on process

- ❑ FFT up to 30th harmonics
- ❑ Model limit: capacitive dark space
- ❑ Calculation of mean values

- ❑ Electron Collision Rate [s^{-1}]
  ➔ Plasma Chemistry
- ❑ Electron Density [cm^{-3}]
  ➔ Plasma Density
- ❑ Sheath Thickness
  ➔ Plasma Stability

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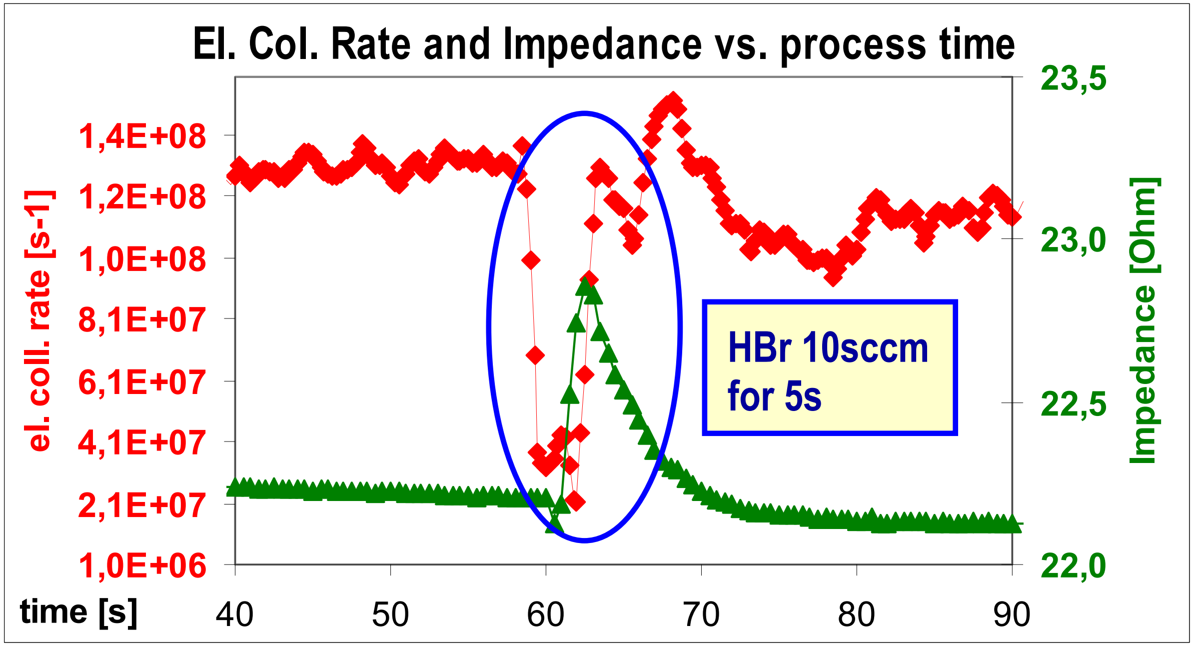
Application Example: Gas Composition Monitoring by Electron Collision Rate ν_e and Load Impedance

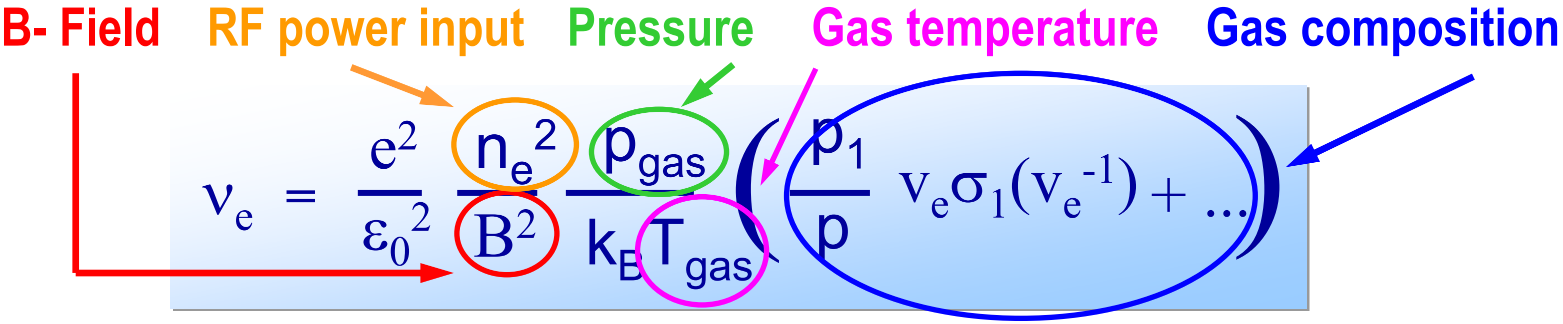


HBr 10sccm for 5s →

Load impedance: change by factor 1,03

Electron collision rate: change by factor 10

Simplified equation of electron collision rate:



$$\nu_e = \frac{e^2}{\varepsilon_0^{\,2}} \frac{n_e^{\,2}}{B^2} \frac{p_{gas}}{k_B T_{gas}} \left(\frac{p_1}{p} v_e \sigma_1 (v_e^{-1}) + \dots \right)$$

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    - ➢ RF Voltage and power measurement
    - ➢ Wafer temperature measurement
    - ➢ Plasma parameter measurement by SEERS
- ❑ **Implementation of in-situ measurement techniques into high volume production**
- ❑ Application of in-situ measurement techniques into high volume production
- ❑ Correlation of tool, process and product parameters
- ❑ Summary

Basic Implementation Requirements

- Reliable data acquisition:
  - Measurement systems need logistic data in real time:
    Lot name, wafer number, recipe, step
  - Merging of in-situ measurement results with tool parameters, inline measurements, tool test results, product parameters and other data
  - Reliably and automatically

- **→ Requirements to etch tool suppliers:**
  - Flexible and open architecture
  - Implementation of standard interfaces
  - Plug & play solutions for optional measurement systems

- **→ Requirements to measurement equipment suppliers:**
  - Implementation of standard interfaces
  - User friendly = automatic data handling

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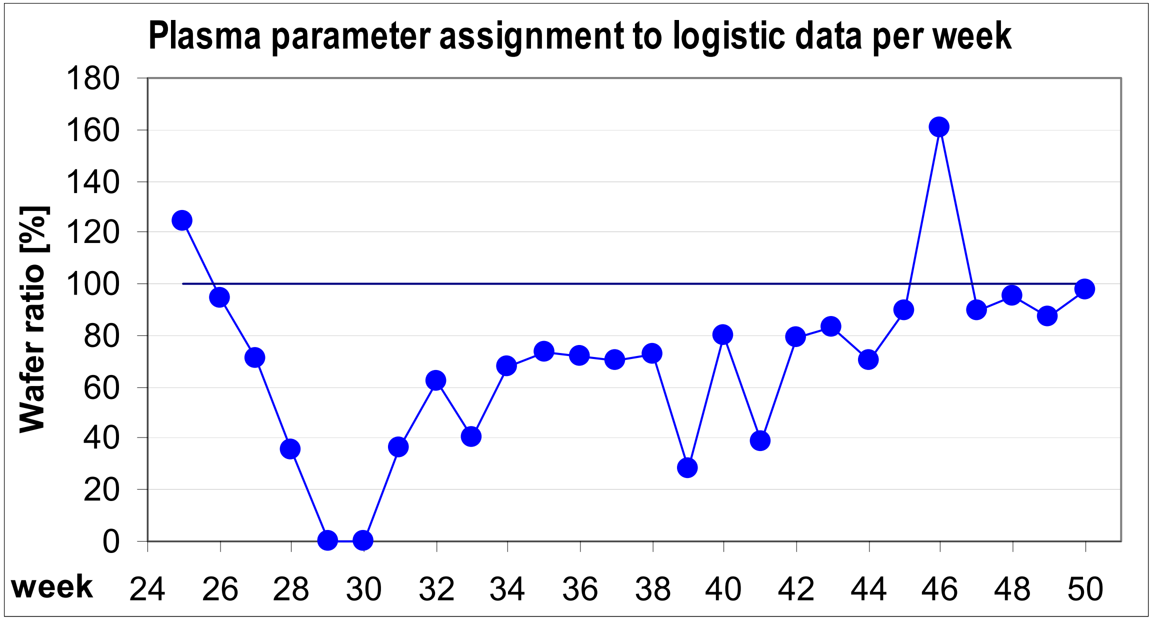
Example of Logistic Data Reliability in High Volume Production



Logistic data reliability of an in- situ measurement system in comparison to tool data reliability

- ❑ Root cause of reliability problem of in- situ measurement system:
  - ➢ Low priority of logistic data interface at mainframe → data loss
  - ➢ Etch tool data interface could not be improved
  - ➢ → Reliability improvement by software modifications of measurement system

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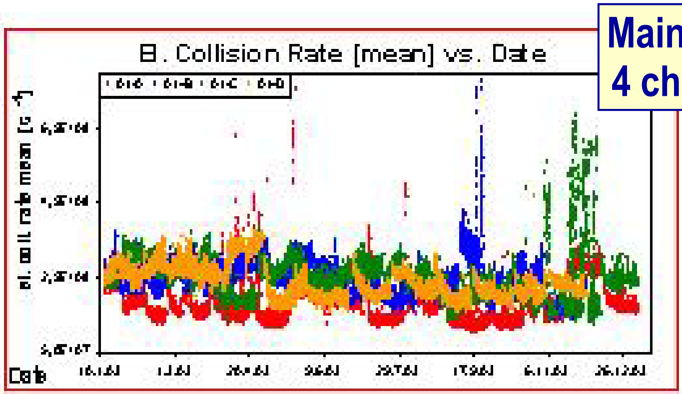
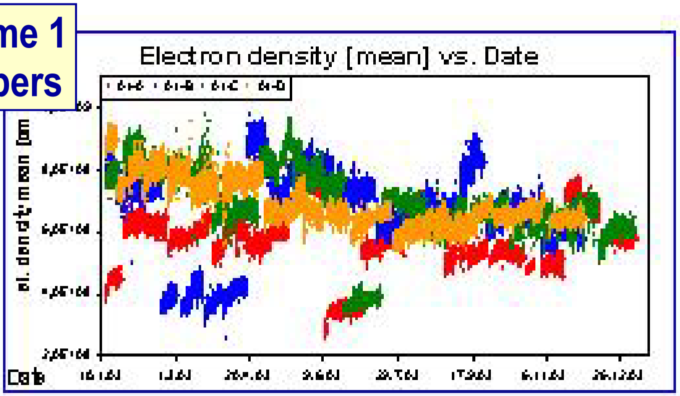
In-situ Measurement in High Volume Production
Example: Electron Collision Rate and Plasma Density

about 237.100 wafers !

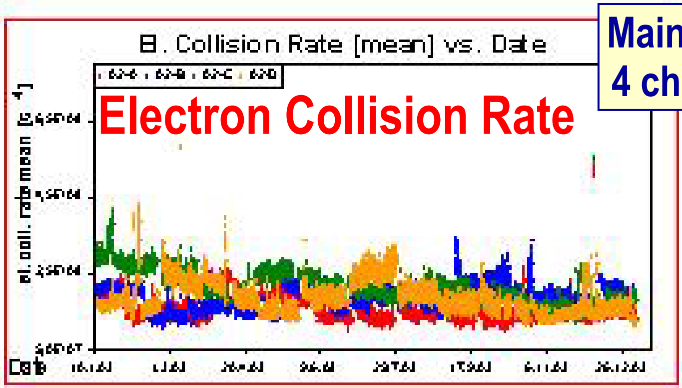
Mainframe 1
4 chambers



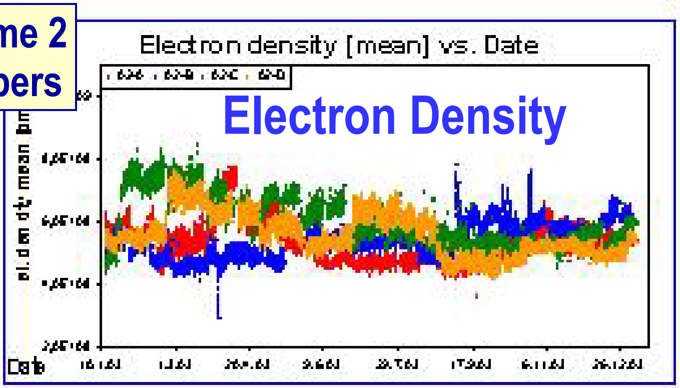


Mainframe 2
4 chambers

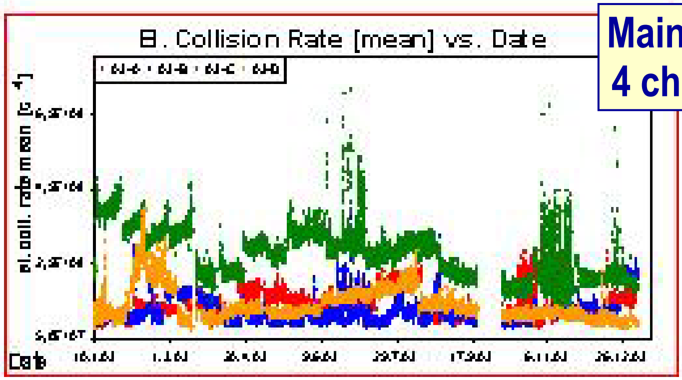
Electron Collision Rate

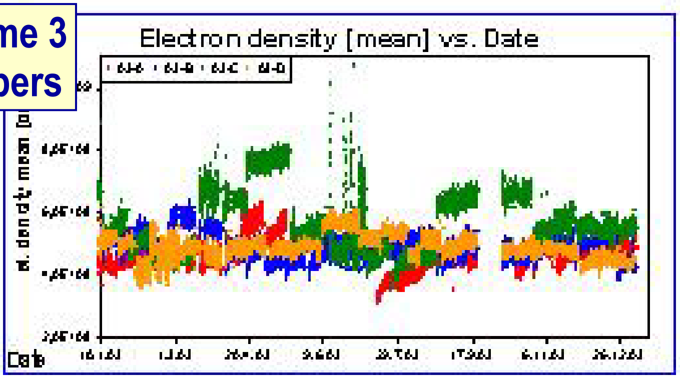


Electron Density



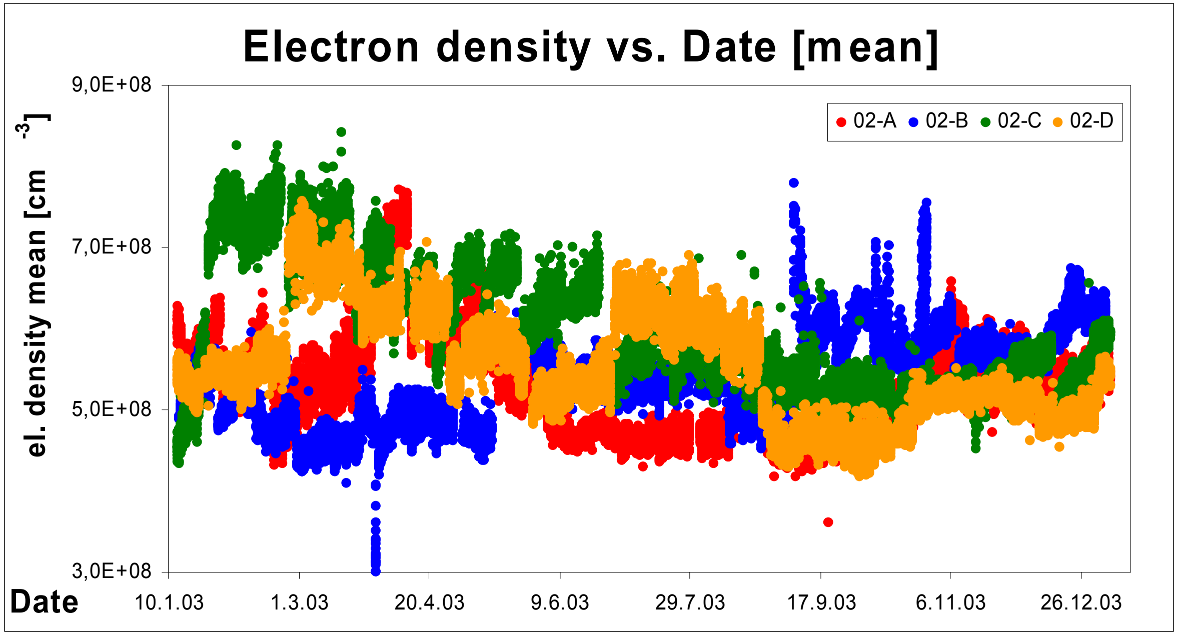
Mainframe 3
4 chambers





Application in production

Electron Density - a Key Indicator of Process Conditions in Plasma with Physical Meaning



Electron density vs. Date [mean]

- Electron density indicates superimposition of long term and short term impacts on process conditions
- Summary of many impacts on process conditions in one parameter → Use as indicator
- Parameter with physical unit and therefore with technological relevance → Use of engineering knowledge for root cause analysis possible

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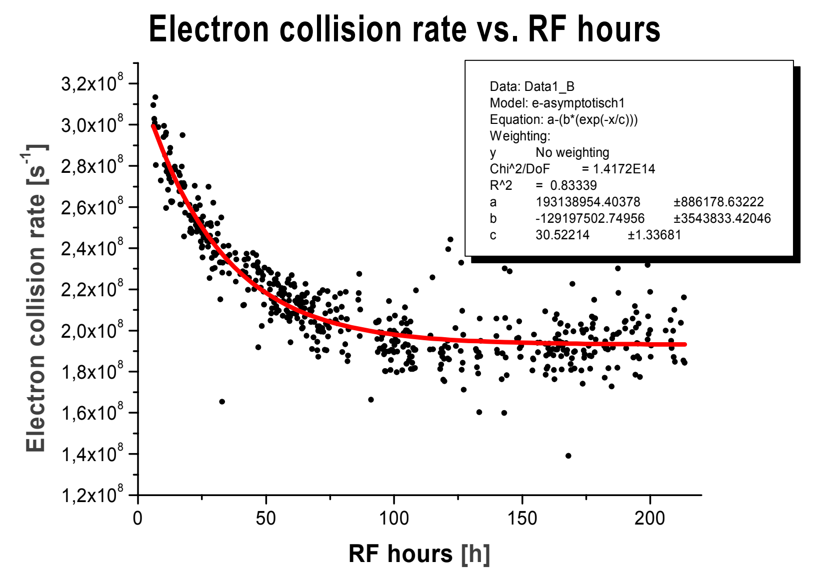
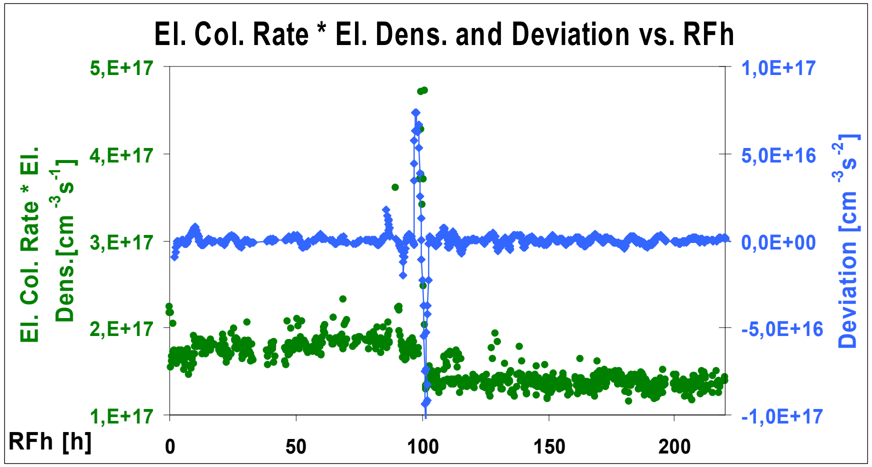
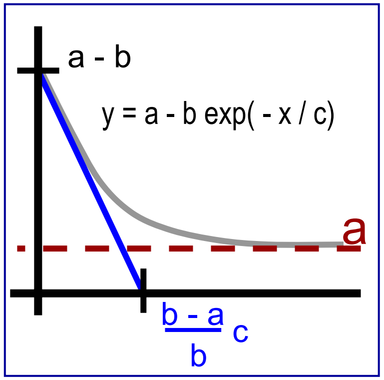
Examples of Simple Numerical Analysis: Exponential Function Fit and Numerical Differentiation

→Poster P106


Electron collision rate vs. RF hours

```
Data: Data1_B
Model: e-asymptotisch1
Equation: a-(b*(exp(-x/c)))
Weighting:
y          No weighting
Chi^2/DoF        = 1.4172E14
R^2       =  0.83339
a          193138954.40378        ±886178.63222
b          -129197502.74956       ±3543833.42046
c          30.52214          ±1.33681
```


El. Col. Rate * El. Dens. and Deviation vs. RFh



a-b → initial value
a → final value
b/c → initial slope

- ❑ Exponential function fit:
  - ➢ Classification of parameter drift after chamber cleans by 3 coefficients
  - ➢ Parameter c: indicates reconditioning time constant in RFh
- ❑ Numerical differentiation:
  → Separation of long term drift and short term parameter variation

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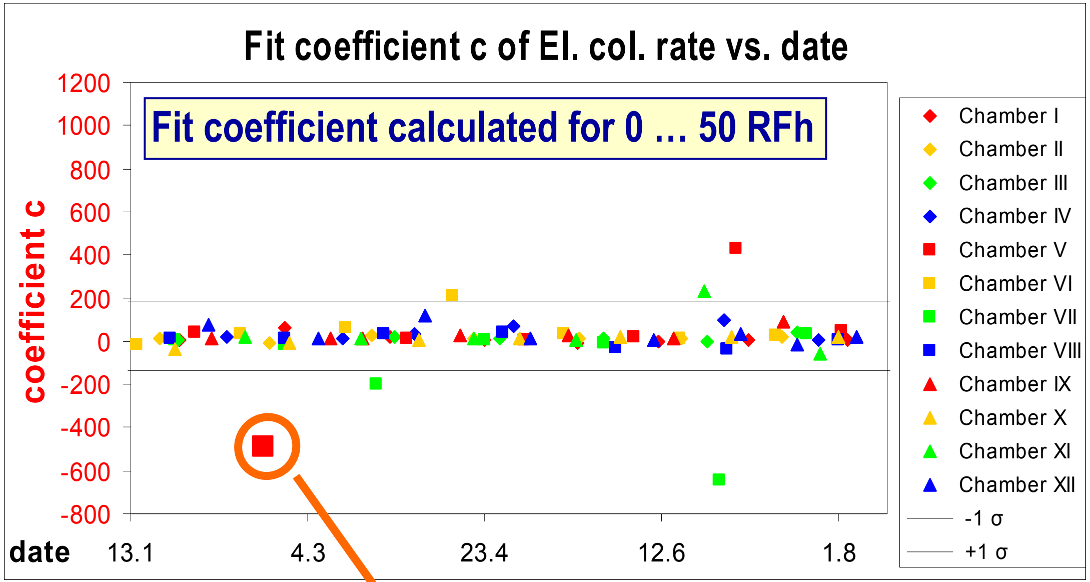
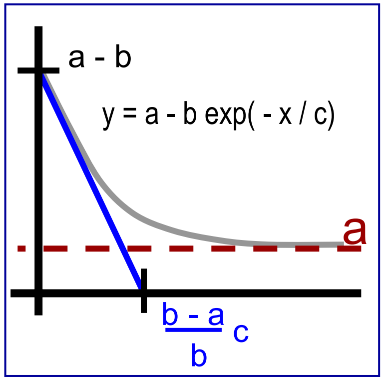
Application Example of simple numeric Algorithm: Wet Clean Classification by Plasma Parameters

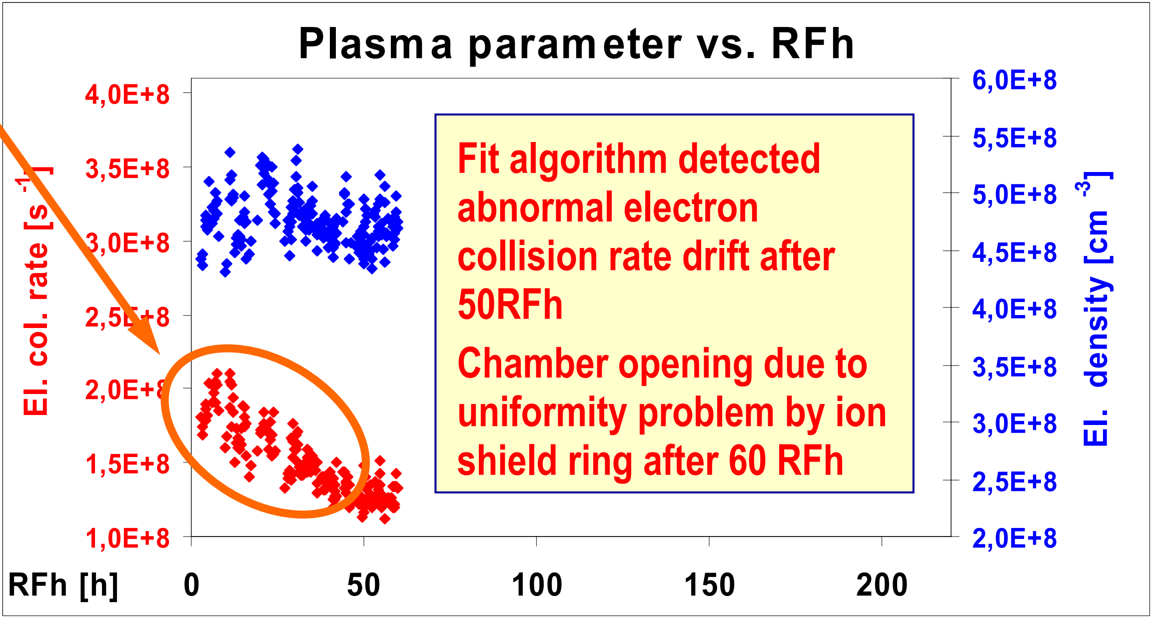


Fit coefficient calculated for 0 … 50 RFh



$y = a - b \exp(-x / c)$

Early and automatic detection of uniformity problem by application of exponential fit on plasma parameters

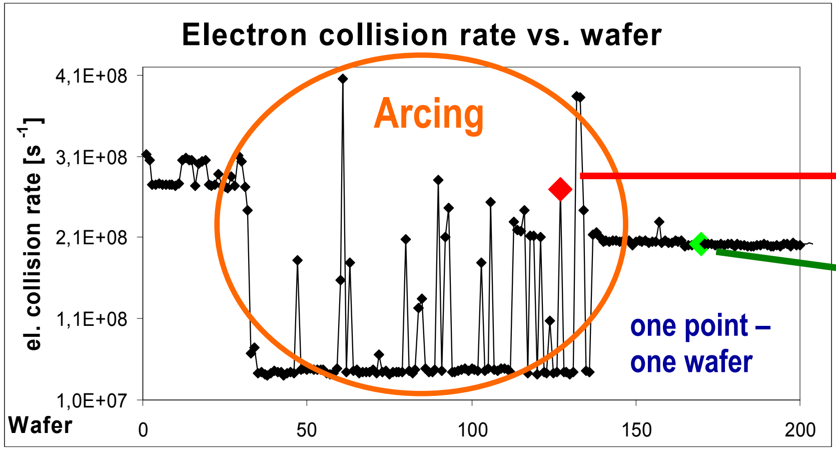


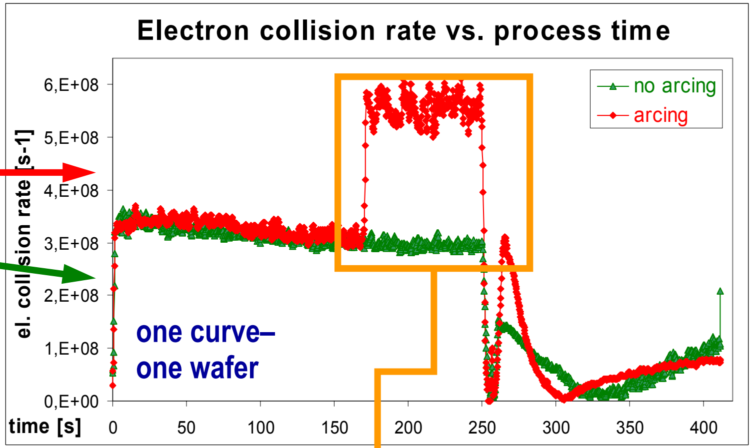
Fit algorithm detected abnormal electron collision rate drift after 50RFh

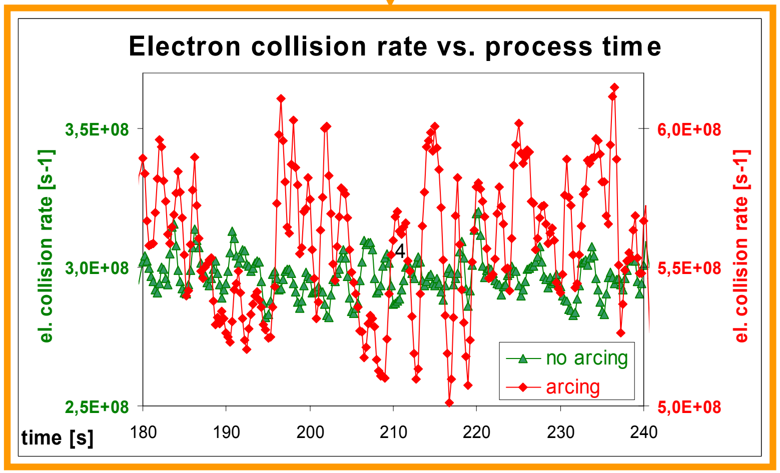
Chamber opening due to uniformity problem by ion shield ring after 60 RFh

Example of Fault Detection and Root Cause Analysis by a Physical Key Parameter: Arcing

➔Poster P609







- Plasma parameter mean values indicate abnormal process conditions → Raw data analysis
- Root cause analysis by:
  - Raw data analysis
  - Physical meaning of key parameter electron collision rate
  - Engineering experience
  - Analysis of additional measurements, e.g., tool parameters

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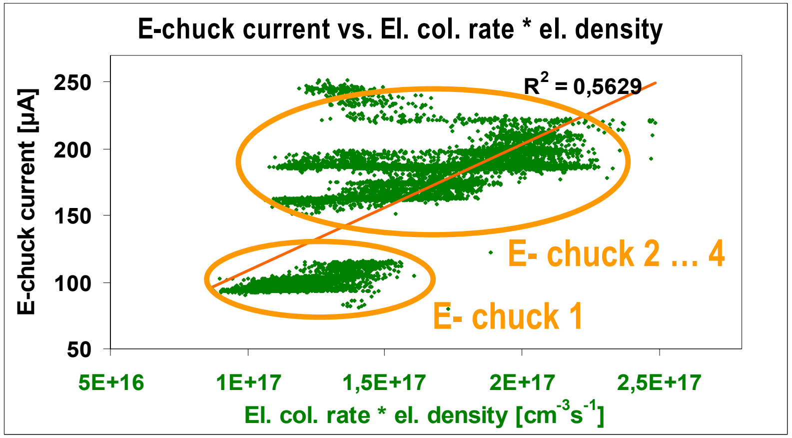
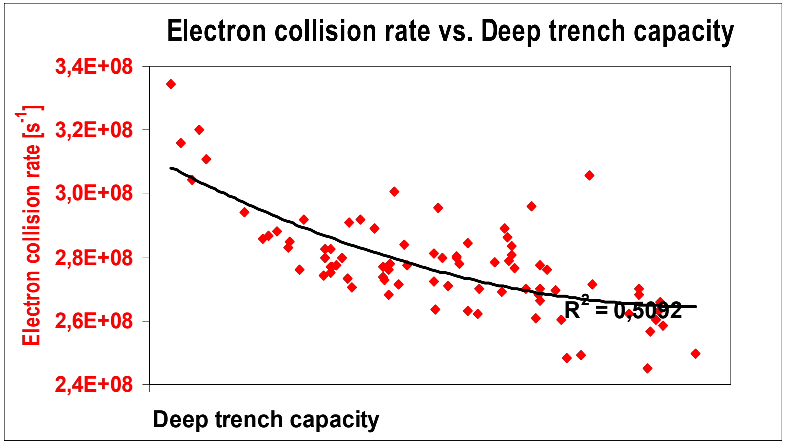
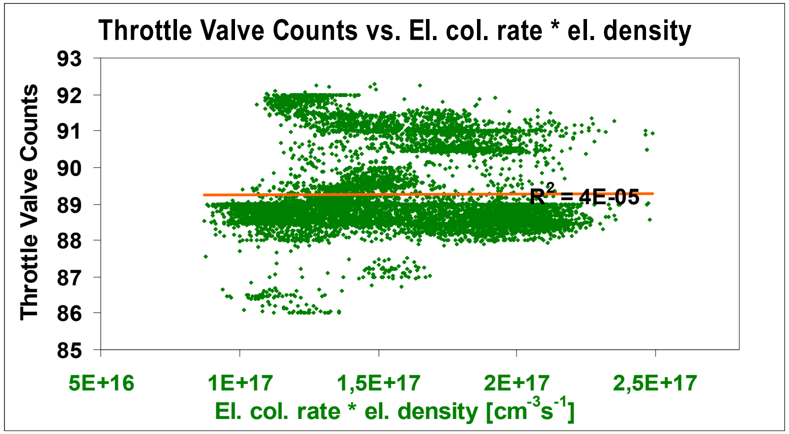
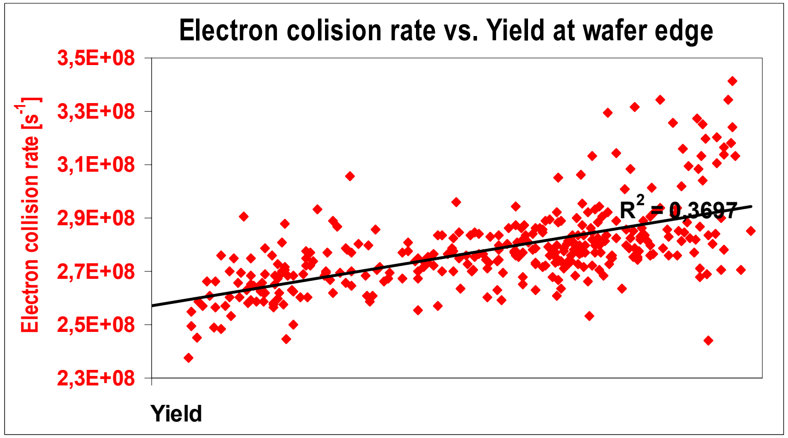
Example of Simple Correlations of Tool, Process and Product Parameters


E-chuck current vs. El. col. rate * el. density


Electron collision rate vs. Deep trench capacity


Throttle Valve Counts vs. El. col. rate * el. density


Electron colision rate vs. Yield at wafer edge

- Simple correlation analysis detects only direct parameter interaction.
- No significant correlation →
  - Tool parameters have no direct impact on process conditions → stable enough
  - Process parameters have no direct impact product parameters → stable enough

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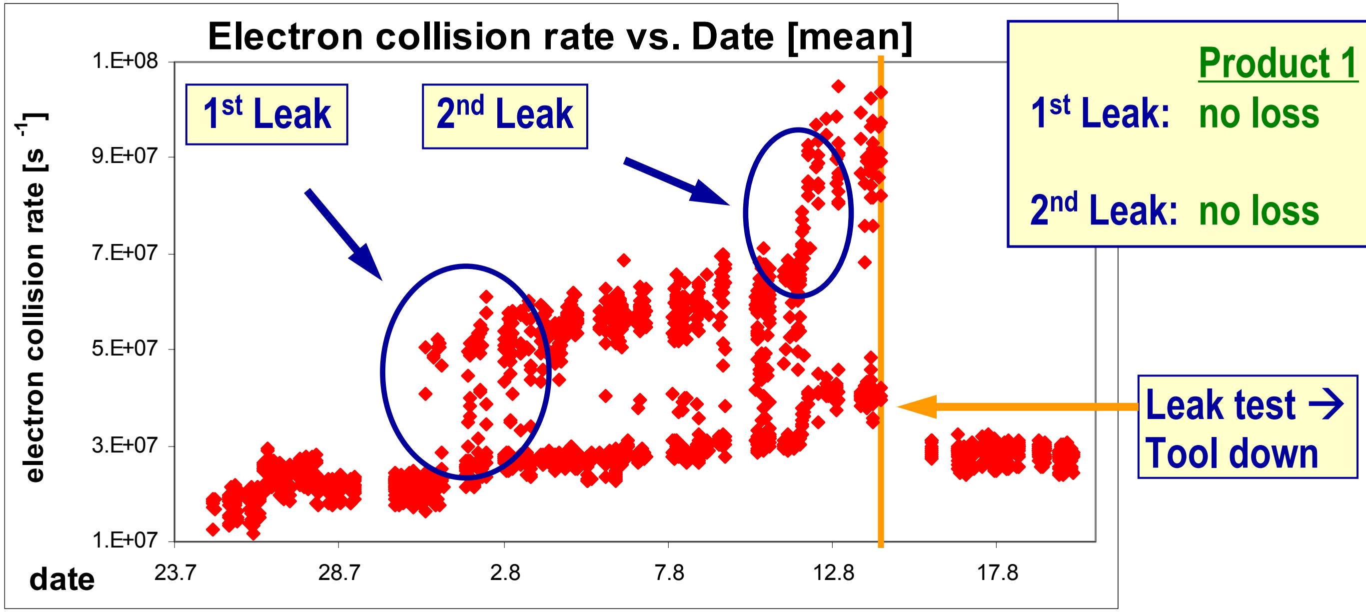
The Meaning of Correlations – How to Control Process Stability ?



	Product 1	Product 2
1st Leak:	no loss	38 lots down grade
2nd Leak:	no loss	4 lots scrap

- ❑ **Impact of tool and process conditions on product depend on product itself !** → How to control process stability ?
- ❑ 1st strategy: According to current product needs:
  - ➢ Advantage: Minimize current process control efforts
  - ➢ Disadvantage: Delay to fix current risk, avoidable risk for future products not fixed
- ❑ 2nd strategy: According to best known methods:
  - ➢ Advantage: Prepared for future products
  - ➢ Disadvantage: Possibly process control over engineering

Summary

- ❑ Plasma processing is characterized by nonlinear high dimensional interactions in a non- equilibrium system. Product wafer surface conditions can not be measured and controlled directly.
- ❑ In- situ measurement techniques, e.g., measurement of RF power, plasma parameters and wafer surface temperature on test wafers reduce this lack of measurements to some extent.
- ❑ Implementation in high volume production requires reliable and automatic data handling.
- ❑ Use of process condition key parameters together with simple numerical analysis, e.g., exponential function fit and numerical differentiation is a simple step for process control improvement.
- ❑ Two main strategies for unit process control:
  - ➢ 1. Control of process conditions related to result of current product
  - ➢ 2. Application of best known methods for process stability and chamber matching

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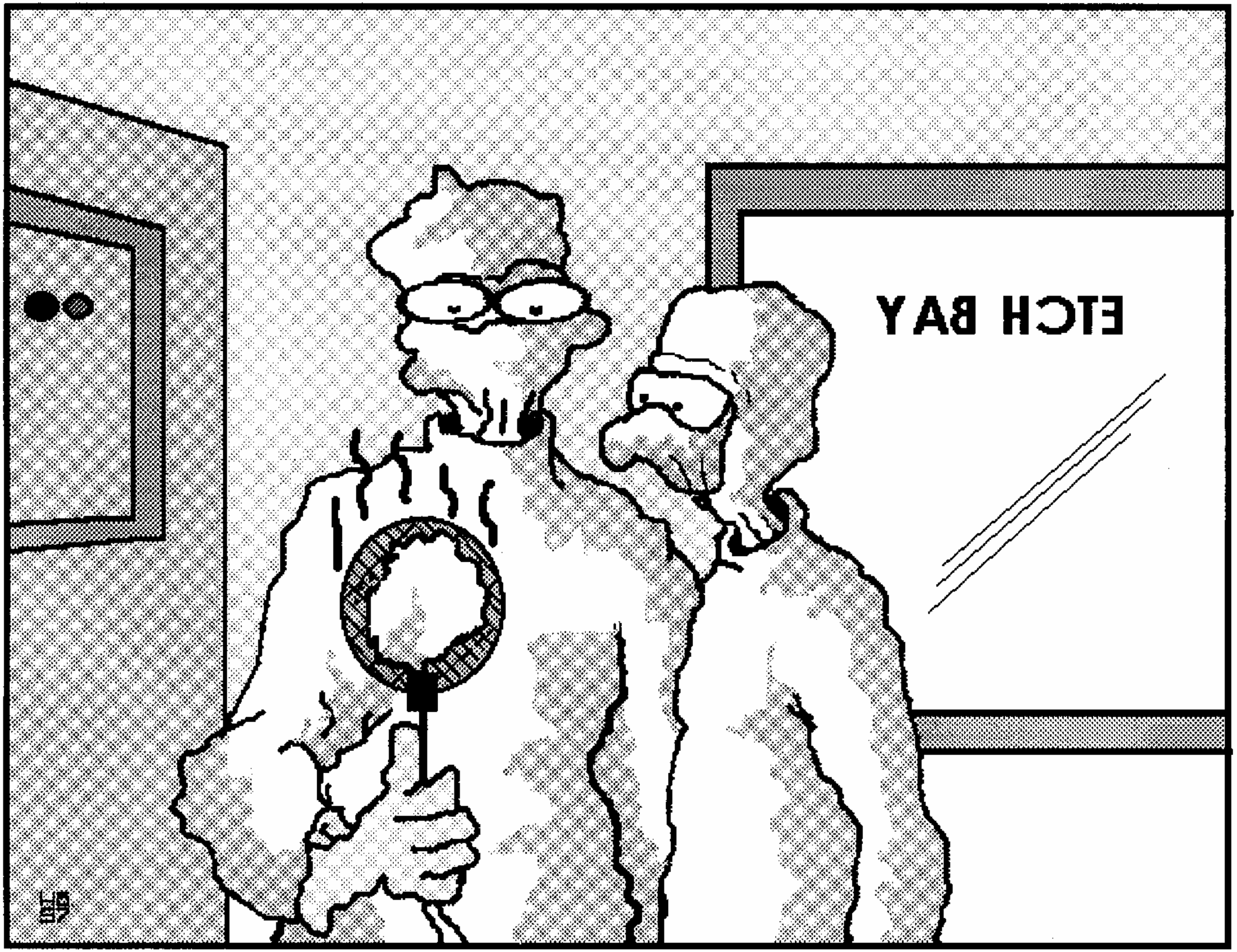

It looks like a LITHO problem...